Senior Thesis

THE MINERAL KAERSUTITE AND ITS OCCURRENCES

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by
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Introduction

Kaersutite is a titanium-rich hornblende. The name was suggested by Lorenzen (1884) for this amphibole which was first found in pegmatite veins and dykes cutting the picrite at Kaersut, East Greenland. However rare kaersutite is, aparently it is more rare than many believe. The name has been used quite loosely for highly titaniferous basaltic hornblende or oxyhornblende (Aoki, 1963). It is usually found in ultra-mafic xenoliths, xenocrysts, and Martian meteorites. In the case of xenoltihs and xenocrysts the host magma is almost always an undersaturated alkaline basalt, and sometimes, more specifically, a basanite. Kaersutite contained in megacrysts of undersaturated basaltic rocks have been reported in Antarctica, Alaska, eastern Australia, souther California, and eastern Africa (Best, 1970).

There have been a few rare occurences of kaersutite in magmas other than this type, these are some of the instances that have been reported: a kaersutite megacryst in tholeiitic andesite and kaersutite from gabbroic xenoliths in trachybasalts (Vinx & Jung, 1977), kaersutite in an olivine tholeiite in Taka-sima & Iki Islands, Japan (Best, 1970).

For the most part kaersutite is thought to crystallize in depths corresponding to the lower crust to upper mantle. It has been noted, however, by Vinx & Jung (1977) at Rosenberg, northern Germany, contained in a basanitic diatreme, pargasite-kaersutite amphibole can crystallize in a wide range of depths, from the main part of the subcrustal lithosphere through the whole crust. An observation from the same locality reveals that mantle derived amphibole in general contains less Ti and more Al than kaersutite of shallow crustal origin. Another important point in the same paper by Vinx & Jung brings to light by noting the fractionation trend with a continuously rising Fe/Mg ratio is a result of successive amphibole crystallization in an evolving magma with falling temperatures. The fact that the possibility of the amphibole being a primary constituent of the upper mantle caught up in the magma is eliminated. It has been determined by Best (1970) that the amphibole-bearing cumulates examined from the Grand Canyon should only be thought of as "second cycle" mantle material. Wilkinson & LeMaitre (1987) conclude kaersutitic amphiboles and titaniferous micas from vein, Group II inclusions and megacryst upper mantle parageneses are directly related to alkaline magnetism in the upper mantle "where they may be associated with incompatible element enrichment of peridotite wall rocks in the immediate vicinity of frozen conduits of alkaline mafic magma." Kesson & Price (1972) offer that kaersutite is considerable in the petrogenesis of alkaline rocks, originally as a possible accessory phase in the upper mantle source regions, and subsequently during fractionation.

Kaersutite Xenocrysts

Kaersutite xenocrysts occur almost always in alkali basalt magmas, and many of these xenocrysts are considered megacrysts. The aluminous amphiboles kaersutite and pargasite commonly occur as megacrysts or xenocrysts in basic alkaline dikes and volcanics. They are also found as a primary phase in some basic and ultrabasic inclusions in alkaline rocks (Kesson & Price, 1972). Righter & Carmichael (1993) suggest a way these megacrysts form in their investigation of alkali olivine basalts containing megacrysts. They conclude that it is improbable that the compositionally unzoned kaersutite megacrysts grew quickly. It is more likely that they grew slowly in a magma chamber, vein, or pegmatite, and possibly precipitated from host magmas. Assuming this, it would take thousands of years for a megacryst to go to 1cm (without compositional zoning). The temperature, pressure and fO_2 would have to remain constant throughout this time period. These necessary conditions may be present in a long-lived magma chamber. Compositionally unzoned kaersutite megacrysts have been investigated in two locations by the authors. The first is the Cima Volcanic Field, the other is Lunar Crater. It is known that volcanism at Cima has been continuous for 9 Ma and 7 Ma at Lunar Crater. Due to these long periods of volcanic activity, we can presume that long-lived magma chambers exist beneath these locations, thus making the above conditions possible.

More work was done at Cima by Colville and Novak (1991). They noted that the amphibole megacrysts from alkaline basalts are exclusively kaersutite. Plagioclase is the most common inclusion in the kaersutite megacrysts, but other inclusions of augite, olivine, and magnetite can also be found. "Some inclusions represent crystals which could have been incorporated within the kaersutite from gabbroic or pyroxenitic wall rock, indicating a spatial and possibly a genetic relationship. It is possible that some of these megacrysts may have crystallized from derivative mobile fluids rich in iron, titanium and alkalis in open systems similar to those found in pegmatite dykes."

Kaersutite megacrysts are also present at two additional locations, the Grand Canyon and Black Rock Summit. At the Grand Canyon kaersutite, clinopyroxene, rare orhtopyroxene and rare olivine can be found. These megacrysts are associated with inclusions made up of combinations of these phases along with spinel. Black Rock Summit is similar. Plagioclase, clinopyroxene, olivine and kaersutite megacrysts are present and associated with inclusions of combinations of the phases listed above together with spinel or magnetite. Due to the likenesses in composition of the megacrysts and inclusions, we can infer that they are related and both are cognate to the enclosing host rock (Best, 1970).

Wilkinson & Hensel (1991) examined an analcime-rich mugearite near Spring Mount in north-eastern New South Wales which contains dominant kaersutite, less anorthoclase and rare Ti-rich mica megacrysts. The most common of the megacrysts are tschermakitic clinopyroxene, feldspars (including anorthoclase) and kaersutite amphibole. Group II ultramafic inclusions such as wehrlites, clinopyroxene and hornblendites were found at some localities. Some of the less common megacrysts include olivine, Al-rich orthropyroxene, Ti-rich mica, apatite, garnet, zircon, corundum, ilmenite, and spinels. The mugearite and megacrysts are isotopically indistinguishable from one another, thus they are cognate. Due to the isotopically distinctive character of the assemblages, the possibility that the megacrysts were incorporated into the mugearite host from earlier magmatic products in the Central Providence is minimized. Anorthoclase megacrysts commonly occur with kaersutite and mica megacrysts in "evolved" mantle-derived lavas. This, also, suggests cogenetic relationships rather than "fortuitious" assemblages of only local significance.

The pressures at which the megacrysts precipitated has also been approximated by Wilkinson and Hensel (1991). "An estimate of the pressure regime of megacryst precipitation is precluded by the absence of olivine and/or tschermakitic pyroxene megacrysts (and related Group II cumulates) and by the wide-ranging stabilities (up to 2.5 GPa) of liquidus or near-liquidus kaersutite, and mica in hydrous alkaline melts. By analogy with the high-pressure crystallizatin of the Anakies nepheline mugearite, the presence of anorthoclase restricts pressures to less than 1.2 GPa and this, assessed in conjunction with the presence of Group I xenoliths suggests that the Spring Mount megacrysts crystallized at pressures broadly equivalent to the mantle-crust boundary (~ 1 GPa)."

Vinx & Jung (1977) examined pargasitic-kaersutitic amphiboles from a basanitic diatreme at Rosenberg, northern Germany. This locality is a small plug with a diameter of 250 m, the vent is filled with Lower and Middle Triassic sediments. They found that megacrysts and polycrystalline aggregates are by far the most common form of amphibole at Rosenberg. They contain more Ti than interstitial and vein amphiboles, maybe indicating somewhat lower pressures at the time and place of crystallization.

Kaersutite Xenoliths

Kaersutite xenoliths are found in many of the same places kaersutite xenocrysts are present. Some of these localities include Lunar Crater, Cima, Dish Hill, San Carlos, San Quintin, and Punta Piaxtle. Righter and Carmichael (1993) found wehrlites (chromian diopside group) and dunite xenolths at Lunar Crater. At Cima, Dish Hill San Carlos, San Quintin, and Punta Piaxtle lherzolites (chromian diopside group) and websterite xenoliths are present. Mantle peridotites, pyroxenites (Type I), aluminous augite (Type II), and gabbroic xenoliths were examined at Dish Hill, Cima Volcanic Field, Lunar Crater, and San Carlos. Olivine, augite, plagioclase, kaersutite, and Fe-Ti oxides make up the gabbroic xenoltihs. It is noted that the Type II veins (aluminous augite, kaersutite, and biotite) are usually preserved only as selvages or at the edge of peridotite xenoliths.

An analcime-rich mugearite near Spring Mount in north-eastern New South Wales, also discussed in the xenocryst section of this paper, contains rare Group I peridotite xenoliths and granitoid inclusions. The presence of these xenoliths in alkaline volcanics is compelling evidence for the ultimate uppermantle origin of their hosts (Wilkinson & Hensel, 1991). A location at

Rosenberg, northern Germany was also discussed in the xenocryst section. A large number of the amphibole xenoliths at this locale are monomineralic and of the others only brown phlogopite is frequently associated with amphibole (Vinx & Jung, 1977).

LeMaitre (1969) studied an area near Tristan da Cunha, South Atlantic were kaerstutite-bearing xenoliths were found. These xenoliths are gabbroic in character. They consist of kaersutite, titanaugite, plagioclase, and iron ore in variable amounts and occasionally biotite and olivine. This occurence is interesting and a little peculiar; to the best of LeMaitre's knowledge, none of the peridotitic or ultrabasic xenoliths that are so common in many of the alkali basalt provinces have yet been found here. Several possibilities regarding the origin of the xenoliths have been suggested:

- The xenoliths are completely accidental and have no genetic relationsihp with the lavas.
- The xenoliths are completely accidental but have contaminated a 'normal' magma to produce the Tristan magma, which is more undersaturated and potassic than most oceanic alkali basalt series.
- The xenoliths are Tristan magmas that have crystallized at depth.
- The xenoliths are the parent material from which the Tristan magma is derived by partial melting.
- The xenoliths are the residue left when the parent material is partially melted to produce the Tristan magma.
- The xenoliths are accumulations of phenocrysts as found in the lavas.
- The xenoliths are accumulations of phases crystallizing from the Tristan magma at

depth.

The last hypothesis is the one favored by LeMaitre "partly by elimination and partly by the facts that the titanaugites probably crystallized under pressures greater than those of the phenocrysts but less than approximately 10 kb and that amphibole+pyroxene+plagioclase is a stable assemblage in some hydrous basaltic melts at pressures greater than 1.4 kb and less than approximately 6 kb. This would place the depth of formation of the xenoliths somewhere between 5 and 25 km."

Wilshire, et al. (1971) examined mafic and ultramafic xenoliths found in volcanic rocks from the western U.S. They found that mafic and ultramafic xenoliths contained in volcanic rocks in this area of the country range in composition from lamprophyric to dacitic and are found in all major tectonic provinces in a very large area from the Coast Ranges in California to the Great Plains. Xenoliths in these volcanic rocks have been placed in eight main groups:

1. Accidental inclusions of crustal sedimentary, igneous, and metamorphic rocks.
2. Gabbroids
3. Metagabbroids
4. Spinel peridotite, pyroxenite, and phlogopite-rich host rocks of the Cr-diopside group
5. Spinel peridotite, pyroxenite, and amphibole-, and mica-rich rocks of the Al-augite group
6. Spinel peridotite and pyroxenite of the bottle-green pyroxene group
7. Spinel peridotite and pyroxenite of the feldspathic ultramafic group
8. Peridotite and pyroxenite of the garnetiferous ultramafic group

For the most part, the spinel peridotite in group 4 is dominant and the rest, including the others in group 4, are very subordinate in abundance. The dikes representing these groups of xenoliths are thought to be products of a broadly continuous episode of melting in the mantle and lower crust and are considered quasi-cognate with the magma that brought fragments of them to the surface.

Kaersutite in SNC Meteorites

Shergottites, nakhlites, and Chassigny (SNC) meteorites are evidently cumulate mafic and ultramafic rocks that crystallized at shallow levels in the crust of their parent body and contain kaersutite and augite found in melt inclusions. The mineralogy and chemistry of these meteorites are greatly like equivalent terrestrial rocks. All have crystallization ages of 1.3 by or younger and formed from magmas produced by partial melting of previously fractionated source regions. Late crystallization ages, complex petrogenesis, and possible evidence in shergottite shock melts have compositions similar to the composition measured in the Martian atmosphere. Development of Martian meteorites may have been accomplished by acceleration of near-surface spalls or other mechanisms not fully understood (McSween, 1985).

Shergottites consist predominantly of clinopyroxenes (pigeonite and augite) and maskelynite (a diaplectic glass of pagioclase comoposition). Trapped melt inclusions in the pyroxenes contain small grains of chromite and kaersutite, one of only two occurences of hydrous amphibole in meteorites (the other is in Chassigny) (McSween, 1985). Treiman (1985) found amphibole (kaersutite with minimal halogen content) and spinel that occur in the Shergotty as magmatic inclusions in pigeonite. The spinel replaces magnetite in the inclusions, and olivine replaces magnetite elsewhere in the meteorite.

The Chassigny meteorite is a moderately shocked olivine achondrite or chassignite with features indicative of a cumulate origin with some subsolidus annealing. Chassigny is an iron-rich dunite (Fo 68) with minor amounts of Ca-rich and Ca-poor pyroxene, alkalic feldspar, chromite, and melt inclusions in olivine. Accessory phases include chlorapatite, troilite, marcasite, kaersutite amphibole, pentlandite, ilmenite, rutile, and baddeleyite (Floran, et al., 1978).

The Nakhla meteorite is an augite-rich igneous cumulate rock. An ultrabasic intercumulus magma is trapped among the cumulus grains and enriched with incompatible elements. Nakhla also contains olivine crystals, the largest of which are probably xenocrysts whose core compositions are too Fe-rich to have been in equilibrium with the intercumulus magma (Treiman, 1986).

Kaersutite in the Egersund Dikes

The Egersund dikes were emplaced 649 +/- 7 Ma as a swarm along a fault system in the Rogaland/Vest Agder Province. They are fine-grained and were intruded at shallow depth (<3km) at a time of regional peneplanation (*ca.* 0.7 - 0.6 Ga) in southwest Norway. These dikes can be traced over distances from a few kilometers to up to 60 km along strike of the fault, and their width ranges from 0.3m to 30m. They are relatively unaltered, contain well preserved olivine and plagioclase phenocrysts and have glassy chilled margins. The magmas in these dikes are broadly tholeiitic in composition, and are classified as olivine tholeiites, tholeiites, transitional basalts, and trachybasalts.

Rounded inclusions in olivine that contain kaersutite, clinopyroxene, plagioclase, and altered glass have been found. The melt inclusions consist of high-Ca pyroxene, plagioclase, amphibole, Fe-Ti oxide together with very rare spinel and apatite in a very fine grained matrix. A sub-calcic amphibole that ranges from kaersutitic to pargasitic to tschermakitic in composition has also been found in these melt inclusions. Compared with kaersutite compositions from mantle-derived xenoliths, melt inclusions in phenocrysts from alkaline rocks, and phenocrysts in alkaline rocks, the Egersund kaersutites have generally lower Si and alkalis, lower Mg-ratios, and high Ca and total Al.

Kaersutite has previously been described as occurring in xenoliths, mineral aggregates, mafic inclusions, as megacrysts, xenocrysts, and phenocrysts in alkaline volcanic rocks, and, less commonly, as intersititial grains and veins in mantle-derived xenoliths. In virtually all of these occurrences kaersutite is inferred to have been derived from the mantle. The mode of occurrence for kaersutite in the Egersund dikes is quite unusual. Chemical differences between kaersutites in the Egersund dikes, and kaersutites in other terrestrial rocks may reflect the tholeiitic composition of the host magma, or different conditions of crystallization (Tefend, 2000).

Conclusion

The mineral kaersutite is usually found in ultra-mafic xenoliths and xenocrysts in an undersaturated alkaline basalt host magma. However, this is not always the case. In two instances, discussed here (and others mentioned briefly), kaersutite is found as inclusions in olvines found in tholeiites. The SNC Martian meteorites (shergottites and Chassigny) and the Egersund dikes both contain this rare mineral which seems to be totally out of its element in these environments. The question still remains, how did these bizarre occurrences come to be?

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